



Bacteria Are Beautiful

by Dianne K. Newman

Above: The widespread use of antibacterial chemicals in common household products could be doing more harm than good (*Annals of Internal Medicine*, 2004, 140, 321–329).

Below: In contrast to the bacteriophobia of the products above, other grocery-store items advertise that they're chock-full of live bacteria. For example, each capsule in the jar on the right contains half a billion live *Lactobacillus acidophilus* and *Bifidobacter* bacteria.

As a microbiologist, I'm appalled when I go to buy soap or dishwashing detergent, because these days it's very hard to find anything that doesn't say "antibacterial" on it. This is disturbing for a couple of reasons. First, there's absolutely no evidence to suggest that these antibacterial versions in any way help to keep our homes cleaner and us safer from disease—in fact, there's some evidence to suggest these products contribute to the spread of antibiotic resistance. And second, it distresses me to see the public given the perception that bacteria are bad and need to be eradicated.

It's a commonly held fallacy that all bacteria are germs, but it's been estimated that out of more than 30 million microbial species, only 70 are known to be pathogens. That's a trivial number. The vast majority are actually doing remarkable things, both for the quality of our life and for the quality of the planet.

How many of you have a glass of red wine with your dinner or begin your morning with yogurt or cheese? These are all foodstuffs that use lactic-acid bacteria for secondary fermentation.

These bacteria have made our lives more enjoyable, but the cyanobacteria have given us something much more important—the air we breathe. They invented oxygenic photosynthesis, by which I mean the process of taking water and splitting it to generate oxygen and power the conversion

of carbon dioxide to carbohydrates and, therefore, biomass.

Over the course of time, these types of cyanobacteria became engulfed by other organisms that then evolved into plants, so the key part of the plant in which the metabolism that generates oxygen occurs,

the chloroplast, is nothing more than an ancient cyanobacterium.

Moreover, we can only breathe this oxygen because our mitochondria—the little organelles in our cells that produce energy—are vestigial microorganisms descended from *another* ancient bacterium.

Microbes are very, very old. They've been on our planet for at least 3.8 billion years, appearing just 800 million years after the planet formed. For the first 1.6 billion years or so of their existence, they had the place to themselves, and it was only after the oxygenation of the air and oceans by the cyanobacteria that the forerunners of plants and animals came along.

Some bacteria have even changed the planet's geology. Microbial metabolism(s) most likely catalyzed the formation of the huge iron-ore deposits known as banded iron formations that occur in various parts of the world, such as the 2.5-billion-year-old Hamersley Range in Western Australia. There have been many of these types of deposits throughout the course of Earth's early history, and we're now beginning to appreciate that the earliest types may have been formed by photosynthetic iron-oxidizing bacteria.

Instead of taking water and converting it to oxygen, which is what plants or cyanobacteria do, these bacteria take reduced ferrous iron (Fe^{2+}) and, in the presence of sunlight, convert it to rust (which contains Fe^{3+}). Over millions of years, this rust accreted into deposits that today constitute the world's major sources of iron ore. (You can read more about this in *E&S*, 2005, no. 4, pp. 10–20.)

How many bacteria are there on Earth today? The father of microbiology, Antony van Leeuwenhoek, appreciated back in the 17th century that there were quite a few. "Though my teeth are usually kept very clean, nevertheless when I view them in a magnifying glass I find growing between them a little white matter as thick as wetted flour," he wrote in 1684. "The number of these animals in



the scurf of a man's teeth are so many that I believe they exceed the number of men in a kingdom."

Leeuwenhoek underestimated: Not only do they exceed the number of men and women in a kingdom, they go far beyond that. We have anywhere from 5 million to 50 million bacteria per square inch on our teeth, and over 700 microbial species living in our mouths. Most of them are aiding us in our digestion—as are the 300 billion bacteria living in each gram of our colon. The palms of our hands have between 5,000 and 50,000 organisms per square inch, although that's nothing compared to the skin of our groin and armpit areas, which has at least 5 million per square inch.

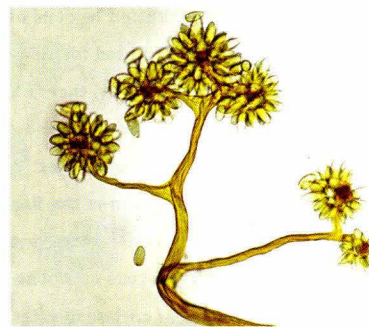
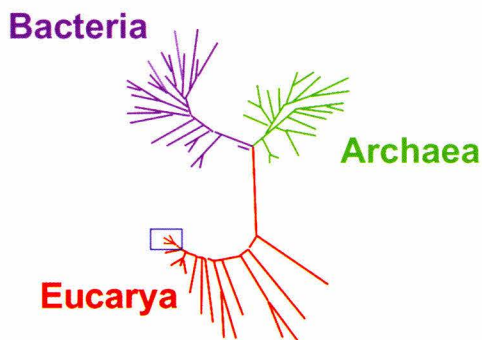
The grand total per person is about 70 trillion (70×10^{12}), so we're really walking vats of bacteria. There are 10 times the number of microbial cells in an adult body than there are human cells, and the gut microbiome alone is estimated to contain more than a hundred times the number of genes that we have in our own genome—so there's a remarkable amount of metabolic diversity living within us. We shouldn't be alarmed by this, however, because most of these bacteria are our friends.

It's a commonly held fallacy that all bacteria are germs, but out of more than 30 million microbial species, only 70 are known to be pathogens.

As well as living on and within animals, microbes live in plants, oceans, rivers, lakes, aquatic sediments, soils, subsoils, and air. The total number of microbes on the planet has been estimated at 5×10^{30} , which is an enormous number. If they were all lined up end to end in a chain, it would stretch to the sun and back 200×10^{12} times.

Microbes are not only ancient and present in vast numbers, they're also very diverse. We tend to think of diversity in terms of plants and animals—the beaks of finches, the wings of butterflies, or the flowers of orchids—but in the “family tree” that shows the relatedness of living things, all the examples that capture our imagination as being representative of diversity are in a small section at the top of the eukaryote branch (below). As

In the universal tree of life based on ribosomal RNA sequences, the organisms we think of as representing diversity of life on Earth—animals, plants, and fungi—occupy the very small area delineated by the blue box. The tree of life is mainly microbial.



Hundreds of thousands of myxobacteria can swarm together to make 3-D “fruiting bodies” whose petal-like capsules are packed full of baby bacteria. This photo of *Chondromyces crocatus* is courtesy of George Barron, University of Guelph, Canada.

you can see, that's just a fraction of the life that is out there. The remainder of the tree belongs to the microorganisms (be they bacteria, archaea, or eucarya).

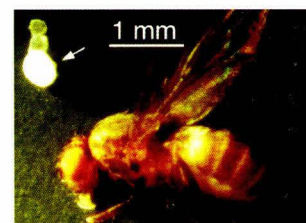
Although they're small, it's a fallacy to think of microbes as just a bunch of rods or spheres. *Thiomargarita namibiensis*, the largest bacterial cell, is about three-quarters of a millimeter across, and strings of them can be seen in shallow waters off the Namibian coast.

This bacterium owes its large size to a central vacuole filled with nitrate, which acts as an electron acceptor to oxidize sulfur.

Myxobacteria develop a “fruiting body” when the population reaches a high density, swarming together to form structures such as the one at the top of the page—not an action typically associated with microbial cells.

The bacteria closest to my heart with respect to their structure are the magnetotactic bacteria, which synthesize magnetite particles in organelles called magnetosomes. (Yes, some bacteria do have organelles.) Aligned in a row inside the cell, these magnetic particles act like the needle of a compass to point the bacterium in the direction of the geomagnetic field. Arash Komeili, a former postdoc in my lab who is now an assistant professor at UC Berkeley, has been studying their ultrastructure and development (see p. 29).

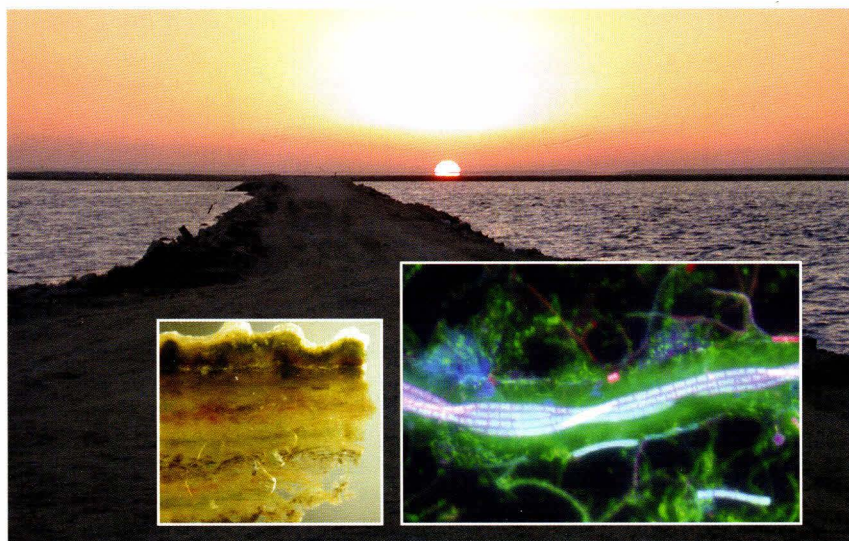
Microbes also have some interesting behaviors. *Vibrio fischeri*, for example, can glow in the dark,



The current record-holder for bacterial size is *Thiomargarita namibiensis*, the sulfur pearl of Namibia. The arrow points to the largest “pearl” in a string of three that is almost the size of the fruit fly's head.

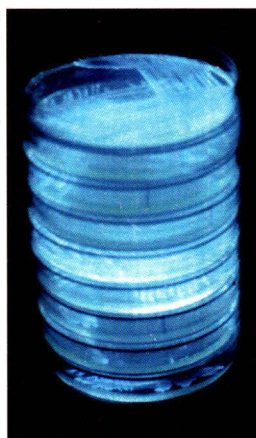
H. N. Schulz et al., *Science*, 1999, 284, 493-495. © 1999, AAAS

Main picture: These seawater evaporation lagoons in Guerrero Negro, Baja California, Mexico, are used for commercial salt production, but below the water, there's a rich biofilm community of salt-tolerant microorganisms attached to the rocks and sand grains. **Left inset:** A magnified section through a microbial mat shows the fine layering of different species. **Right inset:** Some intertwined strands of one of these species, the filamentous cyanobacterium *Microcoleus chthonoplastes*.



See also R. Ley, et al., *Applied & Environmental Microbiology*, 2006, 72, 3685–3695.

J. Leadbetter & K. A. Egland, *J. Bacteriology*, 1999, 181, 2667–2668. © 1999 American Society for Microbiology



E. Ruby, et al., *Science*, 2004, 303, 1305–1307. © 2004, AAAS



The ability of some *Vibrio* bacteria to glow in the dark, even in culture dishes (top), is exploited by the tiny Hawaiian bobtail squid (bottom) to make itself invisible to predators at night. (Photo of squid courtesy of M. J. McFall-Ngai, University of Wisconsin-Madison.)

a phenomenon known as bioluminescence, and often lives in a symbiotic association with the Hawaiian bobtail squid *Euprymna scolopes*. This squid has a terrific strategy. It creates a home for these microbes, called a light organ, where they can feed and grow to a density at which they produce light, something that single cells of *Vibrio* swimming around in the ocean can't do. The squid rises at night to feed in the upper parts of the ocean, but this makes it vulnerable to predators swimming below, because they can spot its shadow. To cope, it uses a counterillumination strategy—the bacteria light up the squid's underside to match the light of the surrounding ocean, which makes the squid “invisible” from below. So these bacteria do a very useful thing for their partner squid.

Some bioluminescent bacteria form such large blooms that they're even visible from space. A bloom the size of Connecticut composed of *Vibrio harveyi* in association with the alga *Phaeocystis* was seen by satellites in 1995 just east of the coast of Somalia. It's now thought that the milky seas described by ancient mariners must also have been caused by this phenomenon.

One of the most fascinating behaviors that microbes have is their ability to live in very hostile environments. Extremophiles, as they're called, like to live in extreme cold or heat, in high acidity or alkalinity, or in places like the Dead Sea or Mono Lake, where the salt is so thick that it's coming out as halite. They can even live on toxic substrates like toluene, benzene, or uranium, converting them to less harmful forms. Such bacteria are very useful for cleaning up waste materials in the environment.

The reason we find microbes almost everywhere we look is because, over the billions of years of Earth's history they've been around, they've figured out how to be fantastic chemists. Their needs are quite simple, because all these single-celled organisms really want to do is to divide. In order to do that, they need two things: energy, and carbon for building biomass. I would argue that metabo-

lism can be thought of as a fusion of two separate processes that provide these needs. The part where energy is generated is catabolism, and the part where biomass is made is anabolism. These parts need to be balanced so that the energy that comes from the substrates, or “foods,” the cell uses is sufficient to power the conversion of simple molecules into cellular constituents and hence biomass.

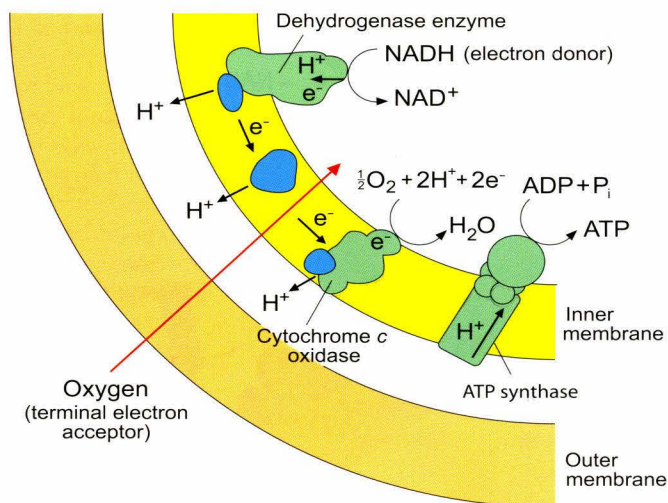
The energy that microbes need can come from many different places. It can come from inorganic chemicals such as hydrogen, hydrogen sulfide, ferrous iron, or ammonium, or from organic chemicals such as glucose or toluene. In addition, energy can come from sunlight. The carbon needed to build biomass can come from inorganic carbon such as CO₂ or from organic carbon.

Many microbes can mix and match these different substrates virtually at will as long as the aggregate provides enough energy. They don't need much, because they can operate really close to the thermodynamic limit for metabolism—in fact, some types of fermenting bacteria have been found to grow where the free energy available is only on the order of four kilojoules. Don't worry about what that means, but trust me—it's really skating a very fine line.

One of the topics my research group is investigating is how bacteria survive metabolically when they're in biofilms. A simple definition of a biofilm is that it's a group of microorganisms attached to a surface. Most people think biofilms are the rings around the sink or bathtub, but that's unfortunate, because they can be very beautiful, like those found in the salt lagoons of Baja California, above. (Admittedly, the biofilm that can form on the surface of our teeth is not so attractive.)

Biofilms are everywhere. They form on the surface of still water, on any solid surfaces in contact with moisture such as river rocks (they're the reason immersed rocks are so slippery), and in the soil around the roots of plants. Bacteria such as *Bradyrhizobium japonicum* even live in biofilms in the root nodules of plants, providing their host with

When *Shewanella oneidensis* respire oxygen, NADH is oxidized to NAD⁺ by a dehydrogenase enzyme sitting in the inner membrane of the cell. This releases hydrogen ions (protons) that cross into the space between the two membranes, while transferring electrons to a chain of (blue) electron carriers. The carriers pass the electrons to the enzyme cytochrome c oxidase, which sends them back inside the cell to the terminal electron acceptor, oxygen. The protons that have accumulated on the “wrong” side of the inner membrane move back into the cell through the enzyme ATP synthase, releasing energy that is used to make ATP from ADP and inorganic phosphorus (P_i).



Which of the steel chips above has a biofilm of *S. oneidensis* growing on it—the clean one or the rusty one? Surprisingly, it's the clean one. *Shewanella* removes corrosion because it uses the rust for respiration.

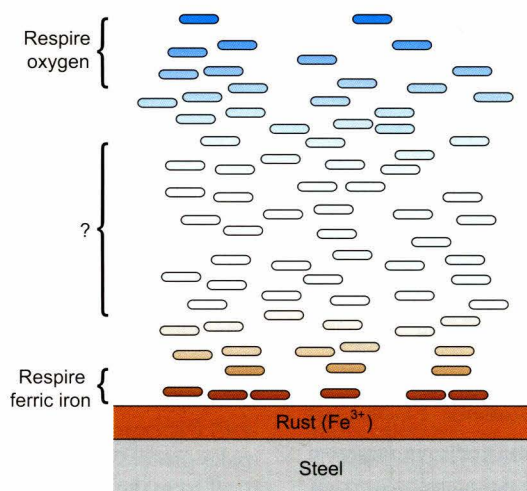
nitrogen they've fixed from the atmosphere.

Bacterial biofilms can corrode the hulls of ships, the legs of oil rigs, and the insides of cooling towers, but a biofilm of the bacterium *Shewanella oneidensis* does the opposite—it removes the rust from steel and keeps it shiny (left). Rust, which is mainly iron oxide, Fe₂O₃, is used by *Shewanella* in its metabolism. This is a very challenging thing for any organism to do, because iron oxides are insoluble and can't diffuse into the cell.

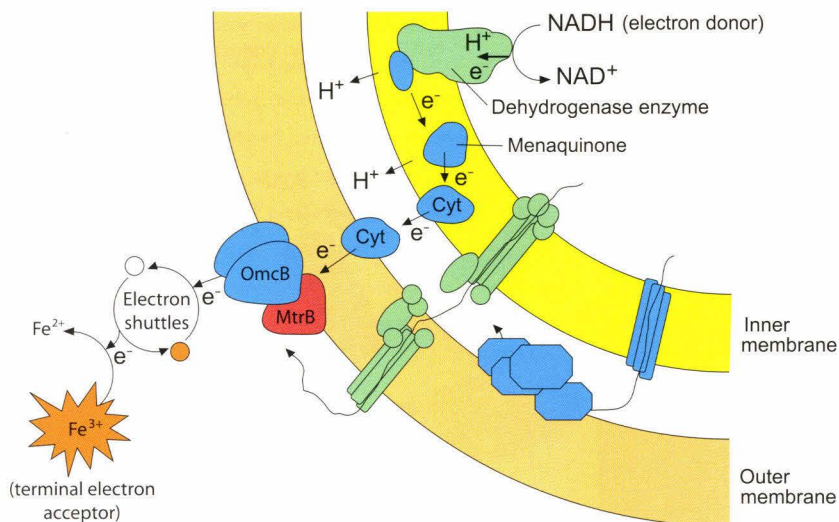
Let me first explain how respiration works when there's oxygen available. *Shewanella* has two cell membranes, an inner and an outer one. This is very similar in structure to a mitochondrion—which, you recall, is our cellular powerhouse. A major goal of respiration is to make adenosine triphosphate (ATP), the “energy currency” of all living things. As outlined in the diagram above, the process begins when an electron donor, such as the reduced form of nicotinamide adenine dinucleotide (NADH), releases hydrogen ions (protons) and electrons upon oxidation by a dehydrogenase enzyme spanning the inner membrane. This enzyme is the first in a

succession of protein complexes embedded in the inner membrane that form an electron-transport chain, which transfers electrons from carrier to carrier while also moving protons from the inner cell matrix into the space between the inner and outer membranes. The chain ends when the electrons reach an enzyme, such as cytochrome oxidase, that takes oxygen as the electron acceptor. In the course of this electron transfer, the protons that have built up in the intermembrane space move back into the cell interior via an enzyme called ATP synthase, and power the phosphorylation of adenosine diphosphate (ADP) into ATP. The electrons, and a few more protons, combine with oxygen to form water—which is why oxygen is called the terminal electron acceptor. That's respiration in a nutshell.

When *S. oneidensis* MR-1 forms a biofilm on steel, the top few layers of bacteria can use oxygen, but it can't diffuse down to the bacteria at the very bottom of the film. To survive, those cells in contact with the rusty steel convert their metabolism to use ferric iron (Fe³⁺) as the terminal electron acceptor. But as I said above, iron, unlike oxygen,



In this conceptual drawing of a section through a *Shewanella* biofilm growing on rusty steel, the bacteria at the top (colored blue) respire oxygen, while those at the base (brown) switch their metabolism to respire ferric iron. The bacteria in the middle of the biofilm, starved of both oxygen and iron, have to be more imaginative in their respiration.



Above: When *Shewanella* uses insoluble Fe^{3+} as the electron acceptor, the electrons released by the oxidation of NADH have to be transported out of the bacterial cell and brought in close proximity to the rust. Electron carriers (blue; Cyt, c-type cytochromes) take the electrons through both cell membranes until they reach the c-type cytochrome OmcB, which transports them to the outside. The electrons either make direct contact with the iron or reach it via small electron-shuttling molecules.

is insoluble and can't diffuse into the cell. So how can it be a terminal electron acceptor? After many, many hours of research both by members of my lab and by others, we think we have now solved the problem, at least at the blueprint level.

Electrons flowing from NADH pass through the dehydrogenase enzyme as before, then via the electron carrier menaquinone to several cytochromes, some of which are embedded in the inner membrane, while others are in the intermembrane space (above). These cytochromes interact—in a way that is not yet understood—with a complex of proteins in the outer membrane, including one called OmcB, a c-type cytochrome with 10 heme groups; each heme contains an iron atom at its center that can do redox chemistry. It's not yet been crystallized, so we don't know whether or not the hemes in this cytochrome come in close enough proximity to the rust for an electron to hop across. Electrons can only hop, or "tunnel," across a very short distance, as Harry Gray, the Beckman Professor of Chemistry, has found.

So we don't yet know whether or not these electrons are transferring directly, but we do know that this protein complex is also capable of transferring

electrons to what I'll call electron shuttles—small molecules that can interact with the microbial cell and be reduced by the electrons coming from it to some state that can then interact with ferric iron and reduce it to ferrous (Fe^{2+}). The shuttles cycle back and forth between the cell and the terminal electron acceptor. They leave the cell to dump their electrons, and then they are taken back by the cell in order to be reduced.

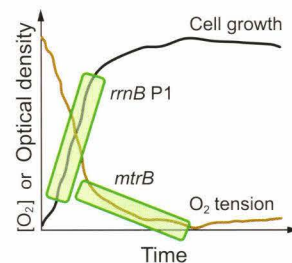
The bacteria at the very top of the biofilm use oxygen, those at the very bottom use rust, but the ones in the middle are stuck between a rock and a hard place in terms of their respiration, because they're too far from either electron acceptor. We wanted to know how they solved this problem. Were they even alive?

To find out, grad student Tracy Teal followed the progression of an *S. oneidensis* MR-1 biofilm as it developed from single cells into large multicellular aggregates. She cultured the bacteria on a glass slide inside a flow cell constantly flushed with nutrients and then added live-dead stain, which stains cells red if they're dead and green if they're alive. As you can see in the photos below left, the cells in the middle of Tracy's biofilm stained red, indicating they were dead.

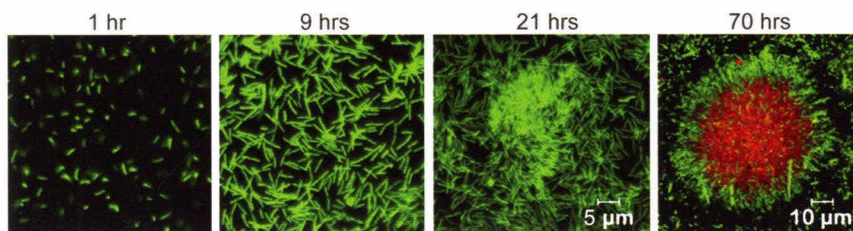
But we had suspicions about the accuracy of this stain, so Tracy went further and developed a way of monitoring metabolism at the single-cell level when the bacteria are swimming freely as single cells, unattached to any surface.

To monitor cell growth, she measured the optical density of the cultures, and you can see from the results in the graph above that initially the density rose rapidly. That's when the bacteria were in an exponential, or logarithmic, growth phase. Later, the growth curve hit a plateau, called the stationary phase, when the bacteria were no longer increasing in number.

To monitor metabolic activity, Tracy followed changes in the expression of two genes. The first, *rrnB* P1, expresses a ribosomal RNA. Ribosomes make proteins, and when bacteria multiply, they need to make more ribosomes, so by monitoring



***Shewanella* growing in a free-living culture increase in number very rapidly at first, as measured by optical density. During this time, a gene that indicates growth, *rrnB* P1, is expressed. As oxygen levels fall, the rate of increase in cell numbers levels out, and the *mtrB* gene that encodes a protein necessary for anaerobic metabolism is activated.**



After *Shewanella* was left to grow on a glass slide for an hour, individual cells started to attach to the base of the slide. After nine hours, they had multiplied and spread over the slide and by 21 hours they were beginning to aggregate into microcolonies. A biofilm had formed after 70 hours. A chemical that stains live cells green and dead cells red suggested that the cells in the middle of this biofilm were dead.

the expression of this gene, we'd find out if the bacteria were growing or not.

To find bacteria that might not be growing, but nevertheless are metabolizing, Tracy looked at a gene that tells us something about what happens as the cultures use up oxygen. As oxygen runs out, a whole suite of genes necessary for anaerobic metabolism is suddenly expressed, including one called *mtrB*, which codes for a protein *Shewanella* has on its surface that is thought to help hold the outer-membrane cytochromes in place.

Tracy labeled her cells with a stable fluorescent protein that was expressed all the time and never faded, but she also used an unstable fluorescent protein that only glowed if the growth gene *rrnB* P1 or the anaerobic gene *mtrB* was turned on. In other words, as long as the bacterium was present, it was red, but if either of those two genes was also active, it turned green.

The results were surprising and exciting. We found that although at this stage the cells in the middle of the biofilm had stopped growing, they were still remarkably metabolically active.

Now we had to find out why the bacteria were expressing these particular genes and their protein products when they were not growing.

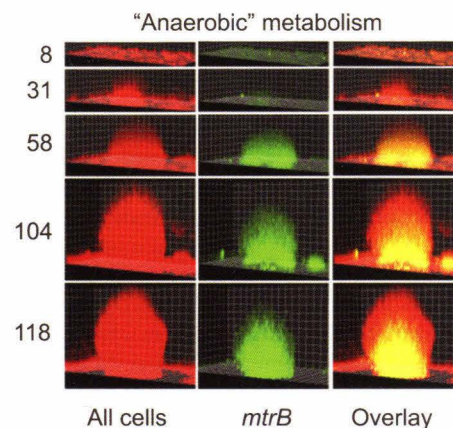
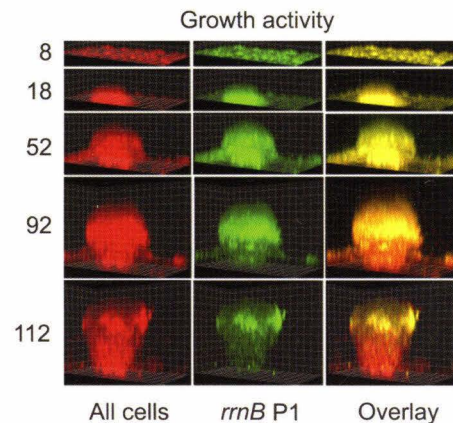
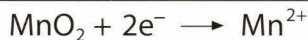
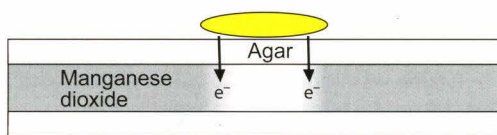
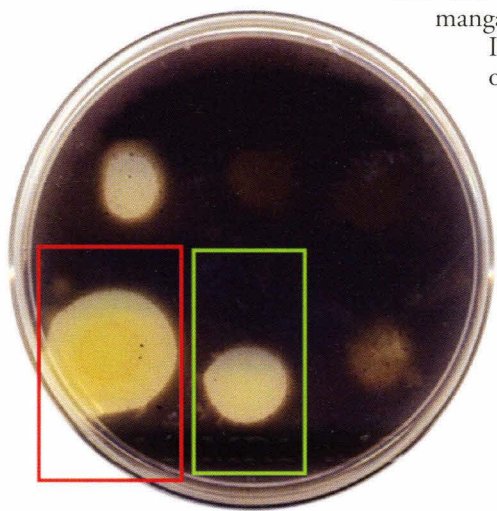
To keep alive, the bacteria have to make ATP, which means they have to keep on doing electron-transfer reactions. So we decided to look for molecules that would indicate that this type of activity was going on. We grew a *Shewanella* biofilm on a clear layer of agar above a black manganese dioxide layer. The agar layer was so thick and dense that none of the bacteria could swim through it, so any changes in the manganese dioxide could only be due to the excretion of some diffusible small molecule that could interact with the manganese.

It worked, as you can see on the left. A light-colored patch appeared in the black manganese layer below the biofilm (green box), indicating that *Shewanella* had released a molecule that had transferred two electrons to the black manganese dioxide and reduced it to a clear form. We also grew a biofilm of another bacterium, *Pseudomonas aeruginosa* strain PA14, on the same culture dish, and as you can see from the size of the clear patch in the red box, it produced something even more effective.

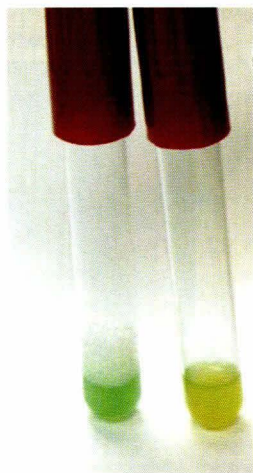
This piqued the interest of two other

Below: The clear agar in the culture dish has a layer of black manganese dioxide (MnO_2) beneath it. When a biofilm of *S. oneidensis*

MR-1 was grown on the agar, it produced a molecule that diffused down to the MnO_2 and reduced it to a clear form, producing the patch in the green box. *Pseudomonas aeruginosa* PA14 growing in another area of the culture dish produced even more of this reducing molecule, judging by the size of the clear patch in the red box.



Biofilms of *Shewanella* fluoresced red at all times, but fluoresced green only when the growth gene *rrnB* P1 or the anaerobic metabolism gene *mtrB* were turned on. The column on the left indicates the thickness in microns (1 micron is 1,000th of a millimeter) of the developing biofilm. Growth activity (top) was initially spread throughout the biofilm, but as the film thickened, there was only growth at the top. The *mtrB* gene was only expressed once the biofilm got thicker (bottom), presumably because the bacteria were switching over to anaerobic metabolism.

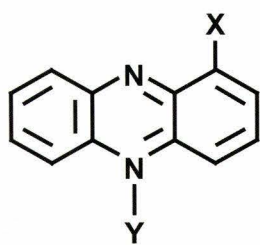


When a colorless culture of *Pseudomonas aeruginosa* was swirled around vigorously to introduce oxygen, the solution turned blue due to the oxidation of phenazine. After the tube was left to stand for several minutes, the solution lost its color again once the oxygen was used up by the respiring bacteria.

members of my lab, grad student Alexa Price-Whelan and postdoc Lars Dietrich. It's been known for over 100 years that pseudomonad species produce beautiful fluorescent molecules called phenazines. Phenazines come in many different forms with different oxidation-reduction (redox) potentials, hydrophobicity (oiliness), and colors. You can see their color very dramatically above. When the phenazine in the colorless culture is oxidized by swirling it around, it turns blue. Left to sit on the benchtop for just a couple of minutes, it will rapidly get reduced by the bacteria and become colorless again. That's redox chemistry in action.

For decades, people have been describing these phenazines as antibiotics because of their ability to react with molecular oxygen to generate free oxygen radicals—a very reactive form of oxygen that attacks and destroys proteins. But in the absence of oxygen, phenazines may be doing something much more interesting. Bacteria lived on Earth long before there was oxygen on the planet—so could these phenazines (or phenazine-like molecules) have played a more fundamental role in those anaerobic days, and do they still, when oxygen is absent, play that role now?

When *Pseudomonas* is grown in a free-swimming culture, phenazines are only produced at the very tail end of exponential growth, at the point at which the bacteria go into the stationary phase. At this point, the bacteria are at a very high density and running low on oxygen, so are they using these phenazines as electron shuttles to power the oxidation of NADH? By coupling the oxidation of NADH to the reduction of phenazines, the cell could be gaining a “last gasp.” I've calculated the free energy that would result from the reduction of several phenazines, and it's always well within the limit that seems reasonable to power microbial growth, or at least to keep the microbes going during the stationary phase.



Phenazines are fluorescent molecules that come in a range of beautiful colors such as deep red, lemon yellow, deep blue, and orange, depending on the chemical groups attached to the X and Y positions of the molecule.

The toxicity of phenazines, and the stationary-phase timing of their production, have long led researchers to malign these compounds in the literature and categorize them as “secondary metabolites.” However, phenazines are made as a branch off a metabolic pathway that leads to the production of many other important things for the cell, and their potential roles in central metabolism indicate that actually, they may not be secondary at all.

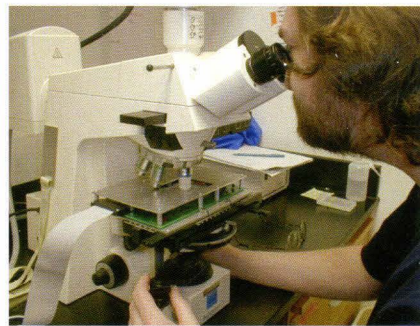
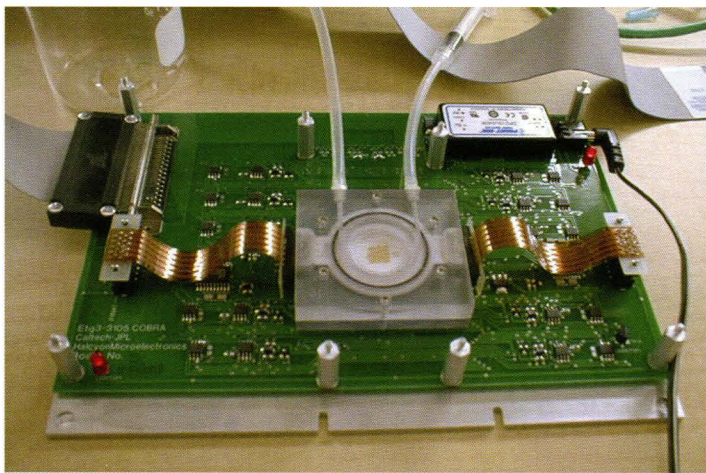
The next step in our investigation was to find out if phenazines are being made in biofilms. We collaborated with Martin Buehler and Didier Keymeulen at JPL to make a really neat biofilm flow cell that we've called the E-Tongue 3, in which nutrients are fed into the chamber through tubes and flow over a substrate chip that contains an array of nine planar electrodes that analyze the chemicals secreted by the biofilm as it grows. The whole circuit board is so small that it can fit on the stage of a microscope.

Using a technique called cyclic voltammetry, we can look for different phenazines in the chamber, as they have very specific “fingerprints.” We focused on one particular phenazine called pyocyanin. When Doug Lies, the senior staff scientist in my lab, grew biofilms of *P. aeruginosa* in the E-Tongue 3, he found that this phenazine was produced only during the late phase of growth, after 144 hours.

We also have some preliminary evidence that the production of these phenazines may play a very important role in the ability of these organisms to aggregate and form a biofilm of significant density. Alexa and Lars made a mutant of *P. aeruginosa* that couldn't make any phenazines and compared its ability to make biofilms with the wild-type strain, PA14. The mutant bacteria didn't aggregate until phenazine was added to the culture, after which they formed a biofilm.

So we're finding that the production and cycling of small molecules such as phenazine antibiotics under times of redox stress—when

The E-Tongue 3 (for electronic tongue) is a state-of-the-art flow cell developed in collaboration with Martin Buehler and Didier Keymeulen at JPL. It enables us to observe the development of biofilms under the microscope (that's senior staff scientist Doug Lies in the photo on the right) while monitoring the chemicals the bacteria use and produce. The cells grow in a culture dish into which nutrients flow in and out over a sophisticated substrate chip that sits in the middle. This chip controls an array of nine planar electrodes that detect chemical changes in the solution.



oxygen is limited and there is no other redox acceptor around—appears to be far more important for microbial metabolism than was previously believed.

Our challenge now is to determine how important this is to microbial survival outside the lab in other areas, such as in our bodies and in the environment, and whether or not these findings apply to any other secondary metabolites. It's going to keep us busy for years to come. □

Dianne Newman joined the geology and planetary sciences division in 2000 as the Clare Booth Luce Assistant Professor of Geobiology and Environmental Science and Engineering, and gained tenure in 2005. She became a professor of geobiology earlier this year, and was also recently appointed a professor of biology. Dianne has carved out a name for herself in the geobiology community with her ground-breaking research into the way in which bacteria have shaped, and continue to shape, the chemistry of their environment, but she didn't start off as a biologist—for her undergraduate degree from Stanford (1993) she majored in German studies and translated descriptions of antiquities into English for the Pergamon Museum in Berlin. She must have decided she needed a complete change from languages, because she then undertook a PhD in civil and environmental engineering at MIT (1997), after which she spent two years as a postdoc at Harvard Medical School working on bacterial genetics. Dianne was named one of the world's top 100 young investigators of 1999 by MIT's Technology Review magazine, and she has gained an Office of Naval Research Young Investigator Award and a Packard Fellowship, but

her greatest honor (so far) was being selected as an Investigator for the Howard Hughes Medical Institute in 2005. She is married to another member of the Caltech faculty, Professor of Chemistry Jonas Peters.

This article is adapted from a Watson lecture given on April 12, 2006.



The members of the Newman group firmly believe that their bacteria are beautiful. From left to right, back row: Yongqin Jiao, Davin Malasarn, Tracy Teal, Yun Wang, and Nikki Caiazza. Front row: Sky Rashby, Christine Romano, Alexa Price-Whelan, and Lars Dietrich. Not pictured are Doug Lies, Itzel Ramos-Solis, and Mike Tice. Team leader Dianne Newman is on the right.